



Achieving zero emission in China's urban building sector: opportunities and barriers

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In recent years, the concept of nearly zero energy buildings (NZEB) has gained wide attention in developed countries. Because of its contribution to achieving full decarbonization in the building sector, NZEB is starting to become a new design target of future buildings and an important means to achieve the 1.5 degrees goal in building sector. This paper reviews the development of NZEB technologies during the past two years (2015–2017) since the IPCC AR5 published and assesses the opportunities and barriers of NZEB in China's urban areas. The analysis suggests that NZEB is feasible in Chinese cities and there is a certain opportunity to achieve zero carbon emission in China's urban area, but there are some limitations and barriers. In order to widely implement NZEB, China should (1) lower the energy service demand in high-rise buildings and consider realizing a high population density with low-rise buildings; (2) promote efficient cooling technologies and the energy saving behavior of occupants.

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Introduction

1.5°C climate change target and building energy consumption in China's urban area

According to IEA's statistics, the buildings sector consumes nearly one-third of global final energy consumption, making it responsible for about one-third of total direct and indirect energy-related carbon dioxide (CO₂) emissions [1]. In China, the building sector has been considered as one of the three major energy consumption

and carbon emission industries [2]. Hence it is a key part of the energy system and a strong component of China's decarbonization plan. The Manila-Paris Declaration calls for the full decarbonization of the world economy, 100% renewable energy by 2050, and zero emissions by mid-century in order to keep the world on track for the target of achieving below 1.5 degrees of warming. For the building sector, NZEB is considered as an important means to achieve 1.5 degrees goal because of its positive impact on realizing zero carbon emission in buildings. Meanwhile, China has realized that its economic development has to be free from dependence on fossil fuels. In 2015 China submitted its 'Intended Nationally Determined Contribution' (INDC) to the United Nations Framework Convention on Climate Change in preparation for the Conference of Parties 21 [3]. China's INDC called for several low carbon actions toward 2030, including a reduction of carbon dioxide emissions per unit of GDP by 60–65% from the 2005 level. A previous study suggested that the building sector could make a large contribution to achieving China's INDC target [4].

This paper provides an assessment on opportunities for and barriers against nearly zero (very low) energy buildings in China's urban areas. The urban building sector refers to the urban residential sub-sector and the services sub-sector. We first evaluate the state-of-the-art technology of nearly zero energy buildings (NZEB) in developed countries. Then we discuss the current status of NZEB in China's urban areas. In addition, we point out major barriers and challenges faced by NZEB development in China and suggest some possible solutions for further implementation of NZEB technologies.

Definitions and energy performances of NZEB

The zero-energy concept has been first introduced and defined in the US in 2007 [5]. Ever since then, zero energy building has been widely accepted as a promising solution to mitigate energy and environmental problems [6]. There are several similar terms and definitions around the world to describe a building with high performance in energy consumption, CO₂ emissions or sustainable aspects [7,8]. IPCC's Fifth Assessment Report (AR5) also pointed out that 'net zero energy buildings' have varying definitions around the world and most of the time the definitions are associated with certain policy frameworks in different countries [8]. For instance, the European Commission introduced the term of 'nearly

zero-energy buildings' for the building sector to achieve the 20/20/20 targets of the EU [9]. In the US, the term of 'net-zero energy buildings' was used in an Energy Independence and Security Act (EISA) report [10]. Moreover, similar terms such as energy plus; fossil fuel free; 100% renewable; zero carbon; and climate neutral can also be found in the existing studies [11]. Nevertheless, a common and universal feature of the high energy performance buildings is that they have on-site or nearby renewable energy systems to balance the energy consumed by the buildings. An important strength that makes NZEB a future goal of low carbon buildings is that it does not compromise indoor comfort. As the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) suggested: 'an energy declaration without a comfort declaration makes no sense', and the European Commission gives specific instructions that energy related benchmarks for nearly zero-energy buildings must fulfill the underlying comfort level [9].

In 2014 IPCC published AR5 [8], which includes a literature review of zero energy/carbon and energy plus buildings in the past decade. In this study, we refer to the buildings with very low energy demand and renewable energy system (on-site or nearby) as NZEB (nearly zero energy buildings) and provide a review on the latest literature of the development of NZEB technologies in the past two years (2015–2017) since the IPCC AR5 published, as well as its future prospects in China's urban building sector. 'State-of-the-art approaches for NZEB in developed countries' section reviews popular NZEB technologies. 'Opportunities of NZEB development in China's urban areas' section introduces existing Chinese NZEB projects and possible solutions for widely implementing NZEB in China's urban area. 'Conclusion' section provides an in-depth discussion of applying NZEB in China's urban area with concentrations on climate and socio-economic circumstances of 31 Chinese province.

State-of-the-art approaches for NZEB in developed countries

As a precondition to achieve net zero energy, a basic feature of NZEB is to have advanced building envelopes and energy efficient operation systems. On-site renewable energy systems are also essential for NZEBs. In the research field of NZEB it is widely acknowledged that zero energy can be achieved through the following three major approaches: passive building design, energy-efficient technologies and renewable energy production technologies [12^{••},13–15].

Passive building design

Passive building design is a design process to achieve very low energy demand for space heating or cooling. It is a valuable approach of NZEB, as NZEB usually requires very low energy demand. For example, the European Commission defined that the energy need for heating and

cooling of a cost-optimal, nearly zero-energy building will be less than 30 kWh/m²/a by 2021 [9]. According to the recast of EU Energy Performance of Buildings Directive (EPBD) [16], a nearly zero-energy building should have a very high energy performance, which can be achieved by advanced passive designs. The IPCC AR5 pointed out that a high-performance thermal envelope can lower the heating load down to 15 kWh/m²/yr irrespective of the climate. As of 2012, Approximately 57 000 buildings complied with this standard in 31 European countries. During the past two years since the IPCC AR5 published, several studies have been conducted from the passive design perspective in European member states including Estonia [17], Italy [18,19], Ireland [20,21], Hungary [22], Lithuania [23], Germany [24], Portugal [25] and Scandinavian countries [26,27].

Major approaches of passive building design for NZEB include space design, the materials used in walls and windows, and buildings' orientation and location [28,29]. In a model simulation case-study, wall/window areas and window-wall ratio (WWR) are selected as representative parameters of passive design [24]. In a comparison study of NZEB and non-NZEB, Corrado *et al.* [19] used different insulation levels of walls, roofs and windows to evaluate their impact on the building energy performance. Congedo *et al.* [28] tested primary energy performance of 256 wall and window combinations with different physical properties and investment costs. Their results suggested that the superficial mass of external walls is important to obtain the best performance in a warm climate (i.e. Italy). With implementation of heat pumps, the best performing combination of wall window can achieve a quite low primary energy consumption range between 76.4 and 77.3 kWh/m²a.

In a warm climate, the main challenge of passive design is to efficiently lower the cooling load. IPCC AR5 suggested that vernacular design is an efficient passive approach to reduce the use of mechanical air conditioning. AR5 also pointed out that even in relatively hot and humid regions such as Southern China, with good passive design, comfortable conditions can be maintained $\geq 80\%$ of the time without mechanical cooling. Huang and Hwang [30] proposed a different opinion in their study of passive design in a warm climate (Taiwan). In their study, five passive building approaches have been assessed by using Givoni's Bioclimatic chart. As a result, they found that although passive solar heating would be quite applicable in the mild winter in Taiwan, during the hot-and-humid season from June to September, passive approaches were not enough to maintain a comfort indoor environment and mechanical cooling was *inevitable*. Schnieders *et al.* [31] evaluated passive houses for different climate zones including subtropical warm climate (Tokyo and Shanghai). Their study suggested in Tokyo and Shanghai, less insulation is needed than in central Europe because solar

radiation levels are greater. During summer season passive cooling could compensate the temperature, but because of the high air humidity levels, more night ventilation would be counterproductive which leads to the need of active cooling and dehumidification. In such regions, overhangs and balconies are preferred because they provide shading in summer without excessive reduction of solar gains in winter. Besides building design, materials can also improve the performance of passive cooling. Saffari *et al.* [32] presented a review of phase change materials (PCM) and pointed out that PCM offers high potential to decrease the cooling energy demand (about 14%) and to improve the indoor comfort condition.

Since most of the Chinese cities have similar climate as Shanghai (hot summer cold winter), NZEB in urban China should consider both passive solar heating and design/materials that reduce cooling energy demand during summer.

Energy-efficient technologies

Energy-efficient technologies refer to services of heating, ventilation and air conditioning (HVAC), domestic hot water (DHW) and lighting. Typical efficient technologies that have been applied in NZEB including solar water heaters [33–35], light-emitting diode lamps [36–38] and combined heating and power [39–41]. Solar water heaters are a popular choice of DHW technology in NZEB partly due to their low investment cost. However the efficiency of a solar water heater can be compromised under night or overcast sky conditions and it is therefore recommended to integrate it with a thermal energy storage system [35]. LED lighting has been adopted in most NZEB for their long service life and good lighting efficiency, despite their expensive price compared with other traditional light bulbs [38]. The combined heating and power (CHP) system is not applied in all NZEBs. Sometimes biomass-based CHP systems are recommended as energy systems to reduce dependency on onsite solar energy in NZEB, especially in areas with sufficient biomass supply. In such cases, a centralized CHP is a better solution than a stand-alone CHP for achieving NZEB [39].

For urban China, solar water heaters are technology prospects to be adopted by NZEBs as they have already been implemented in many households. LED and CHP are also favorable technology options with consideration to their potential disadvantages discussed above.

Renewable energy production technologies

In order to achieve 'nearly' zero energy or even 'net' zero energy, an on-site renewable system is the most essential feature of NZEB. A majority of NZEB use solar photovoltaic (PV) panels to generate renewable energy supply [42–45]. In some cases wind turbines are installed in NZEBs as supplemental generation devices to form a PV-wind hybrid system [46,47]. However, the existing

renewable energy production technologies are still very unstable. Zhang *et al.* [6] pointed out that due to the uncertainties associated with the renewable system energy generation and building energy consumption, NZEBs are liable to fail in achieving such an annual energy balance. Because the PV panels can be easily effected by environmental factors (e.g. weather, atmospheric conditions), the power generation ability of renewable energy systems are often overestimated during the design stage of NZEBs, directly leading to an insufficient energy supply during the operation period [7,36]. Furthermore, in areas with a warm climate, electricity generated by PV panels may not be enough to satisfy the cooling load during summer. In order to realize NZEB, a newly developed technology, the smart photovoltaic system blind (SPSB) was proposed to generate electricity in the PV system and to reduce indoor cooling demands through the shading effect in the blind system [48]. Combining the SPSB with the PV panels can improve the energy self-sufficiency rate to 1.25–2.31 times superior to other alternatives.

Furthermore, implementing thermal energy storage in building allows to increase contributions of solar and aerothermal energy, by overcoming the time mismatch between demand and supply [49]. Sensible and latent heat storages are both widely used techniques for building applications, in which the latter has good performance in free-cooling ventilation systems, solar energy storage solutions, and demand-side management strategies which makes it a crucial application to achieve NZEB. Hsieh *et al.* [50] considered energy storage as a critical component that can be used to enhance the performance of solar thermal energy systems. But they also pointed out that large storage volumes could face the risk of lower system efficiencies due to greater losses for charging and discharging, and transmission and sensible heat losses during the storage period.

In case of China's urban area, PV system with thermal energy storage is undoubtedly an essential requirement of NZEB. Also, the disadvantage of low surface-to-volume ratio of high-rise buildings can be compensated by installations of the smart photovoltaic system blind.

Opportunities of NZEB development in China's urban areas

NZEB projects in China

NZEB development is still in its initial stages in China. The majority of existing studies focus only on theories and model simulations. Tian *et al.* [51] investigated the possibility of achieving NZEB in a northern urbanized city in Beijing by using TRNbuild software to establish a 12-story residential building model for energy performance evaluation. The results indicate that in model simulations it is possible to achieve nearly zero energy in Beijing's residential buildings as long as the buildings

are well designed with passive methods, and installed with a solar hot water system, air-source heat pump, and a photovoltaic system. Energy consumption of heating and cooling in such building is 11.1 kWh/m²a, a 63.4% reduction compared to the reference building (without NZEB technologies). Energy performance of high efficiency domestic hot water system in the building is 8.43 kWh/m²a, while electricity output of solar rooftop photovoltaic system is 18.71 kWh/m²a. This indicates that PV system is able to provide 95.8% of electricity for heating, cooling and domestic hot-water. Similarly, Li *et al.* [52] used a building energy consumption software DeST to simulate the NZEB energy performance in a two-story public building in another northern Chinese city, with less urban population density than Beijing—Shengyang. The results show that passive building design (three-layer low-e windows and external wall thermal insulating technology) can cut 64% of the heating load.

Compared to the simulation studies, there are far fewer studies that concentrate on measuring real buildings. Taking a real building in Tianjin (a highly urbanized northern city) as research subject, Zhou *et al.* [53•] analyzed the annual operation energy consumption of a two-story public building in Tianjin. The results showed that energy consumption of the case study building was much higher than the energy generated from the solar PV system. Their conclusions are consistent with the case study research in developed countries [7•,36], which also discovered underestimates of energy consumption at the design stage. According to Zhou *et al.*, the mismatch is mainly caused by occupants' behavior and the atmospheric environment constraints to use the solar PV system. Therefore, to successfully promote NZEB in China it is crucial to accurately simulate energy performance that reflects the actually occupied building during the design process. The economic perspective is also important for implementing NZEB. NZEBs certainly cost more than conventional buildings, however, previous research suggests that NZEBs have a realistic payback time. NZEB case study in Tianjin [53•] revealed that the building costs RMB 17 300 yuan/m² to construct (e.g. PV system and insulating windows), which is 70% higher than that of an ordinary energy efficient building. Still, the cost can be balanced out from energy savings. The case study building is able to achieve about 27.4% more energy savings than conventional buildings. The payback period is about 9 years.

Major barriers and suggested solutions

High rise building and urban form in China

NZEB is a good marketing tool, because it implies a goal of autarchy, which is attractive to many people. However, from a sustainable energy systems perspective, it may not always be possible or even useful to try achieving it; high-rise buildings are the most prominent example. As IPCC pointed out in the AR5 report, NZEBs face limitations due to height and urban density [8]. Pan and Li

conducted a cluster and exemplar study on the feasibility of NZEB [7•] with different numbers of floors in different climate areas. Their study also pointed out that NZEB technologies are not feasible for application in high-rise buildings due to the higher energy demand and geographical constraints to the use of renewable technologies (e.g. the low surface-to-volume ratio of high-rise buildings). Currently in urban China most of the buildings are medium to high-rise. Researchers have suggested the possibility of a 12-story residential NZEB in a model simulation [51]. However, in reality, China's existing NZEB projects are a two-story public building [53•] and a single story residential building [54], which are not likely to be promoted in urban China on a massive scale. Since researchers are still looking for an efficient method to increase the power generation capacity of renewable energy system in high-rise buildings, it is important to lower the energy service demand through efficient HVAC devices and energy saving behavior among the occupants [7•,36,53•]. On the other hand, Cheshmehzangi *et al.* suggested the possibility of realizing a high population density with low-rise buildings in an eastern Chinese city—Ningbo [55•]. It is worth reconsidering the urban block design in China, since 'high densities may be achieved in quite low rise buildings' [55•].

NZEB in a warm and humid climate

The great challenges of building NZEBs in warm areas will be to meet the very low annual energy balance required by NZEB. Most of the passive design aims to improve the insulation envelope while efficient technologies aim to lower the heating or cooling/dehumidification service demand. China can be divided into five climatic areas for designing the built environment, and in hot-summer/warm-winter areas cooling service contributes to most of the urban building energy consumption as well as CO₂ emission [56]. As introduced in 'NZEB projects in China' section, currently both simulation and field survey studies of Chinese NZEB are concentrated in northern cold areas [51,52,53•]. Although in a warm and humid area it may be easier to provide the energy required by the building on site (without a seasonal storage with its high losses and high cost), it is more difficult to produce the energy used in the course of the year on site due to often cloudy skies during periods of high humidity and temperature. Thus efficient cooling technologies based on renewable energy are crucial to developing NZEB in a warm climate. Solar cooling is considered as a desirable cooling technology for NZEB as it can be powered directly by photovoltaics (PV) [57]. However, solar cooling requires rather high investment costs and a long payback time, which will make it hard to widely implement in China. Instead, Al Ajmi *et al.* [58•] suggested that a PV system integrated with efficient chillers (e.g. high COP water-cooled chillers) is an economic alternative for NZEB in warm climates. From the

passive design approach, efficient building shell can reduce the cooling load caused by energy (i.e. solar heat) entering from walls and windows. Previous studies reviewed in 'Energy-efficient technologies' section provide insights of passive cooling in a warm climate. For instance, in a Chinese city with mild climate (Shanghai), overhangs and balconies are preferred for residential building [31]. In another study of PCM's application in five main climates [32], it is suggested that for warm regions in China (climate zone C: warm temperate), adding PCM to the inner surface of vertical walls could significantly improve the annual cooling energy performance and reduce discomfort hours. Besides the designs and technologies, occupants' behavior such as turning off chillers during non-occupied periods, proper schedules for lighting and equipment operation will also contribute to making a reality of NZEBs in warm climates.

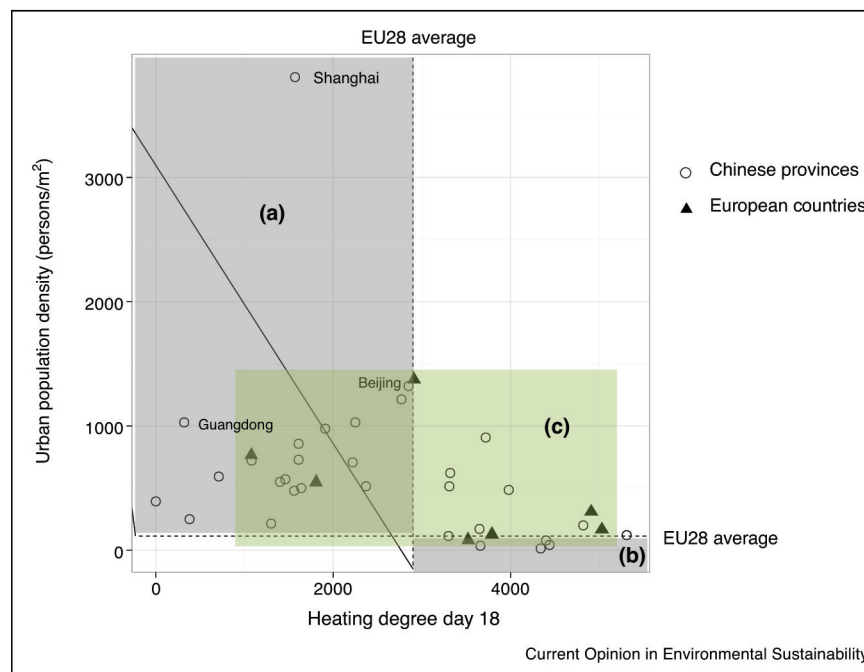
Conclusion

NZEBs are gaining increasingly wide attention and interest for realizing full decarbonization in the building sector. Nearly zero energy is starting to become a new design target of future buildings for achieving the global 1.5 degrees goal. There are already several successful NZEB projects constructed in developed countries. Figure 1 shows the urban population density [59] and heating degree day 18 (HDD18, [60]) of 31 Chinese provinces. European countries whose NZEB projects are reviewed in 'State-of-the-art approaches for NZEB in developed

countries' section are also plotted in Figure 1 [61]. According to our literature reviews, NZEB technologies are widely adopted in cold and less populated environments (B area in Figure 1) as most of the European exemplars fall into this area. Whereas in China's urban area, development of NZEB should concentrate more on cooling and dehumidification needs in order to cope with the warm climate and high population density (A area in Figure 1). A positive prospect of achieving NZEB in China is that a majority of the Chinese provinces (26 out of 31 provinces) actually fall into the green area (C area in Figure 1) where NZEB has been successfully achieved in EU countries under countermeasure targets or regulations (e.g. EPBD recast) irrespective of the climate conditions. This implies that with proper policy pushes (e.g. emission reduction goals, efficient target levels) and passive design solutions (e.g. the ratio volume surface; the orientation of buildings), NZEB is feasible in Chinese cities. With efforts to overcome barriers, there is a certain opportunity to achieve zero carbon emission in China's urban area. Regarding the aforementioned barriers, we suggested the following two solutions for further development of NZEB in China:

- (1) Certain solutions are necessary for realizing NZEB concept in high-rise buildings. It is crucial for China to lower the building energy service demand through passive design and energy-efficient building shells, efficient HVAC devices and energy saving behavior

Figure 1



Barriers of NZEB in urban China.

among the occupants, and furthermore to realize a high population density with low-rise buildings.

- (2) Developing NZEB technologies in China should focus not only on the energy performance of heating services but also on cooling services. Energy-efficient design, passive cooling, and efficient cooling technologies based on renewable energy are crucial to developing NZEB in a warm climate. To lower the cooling service demand, energy saving behavior among occupants in buildings is important as well.

To conclude, in order to promote NZEB and achieve zero emission, which is required under the 1.5 degrees goal, in high density Chinese cities, it is firstly essential to set well-suited implementation goals and policies for NZEB in major urban cities. Next, to achieve these targets, it is important to minimize energy demand through energy efficiency and user behavior, and then maximize the use of building-integrated renewables, as long as both is economically reasonable. It is favorable to realize a high population density with low-rise buildings than with high-rise buildings. However, balancing demand and renewable energy supply should still be considered on a regional level. A regional renewable energy assessment would allow consideration of potentially more effective off-site renewable resources in addition to on-site rooftop or façade systems.

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- of special interest
- of outstanding interest

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